Optimizing Site Selection for Stormwater Recharge

(Assistance ID No. X7-97167501)

Final Report

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May 31, 2009

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Introduction

Many urbanized Massachusetts water bodies are impaired by stormwater runoff. Strategies to manage stormwater and reduce water stormwater impairments often require the application of stormwater controls throughout a watershed. Infiltration or recharge methods are of particular interest for stormwater controls because they have numerous benefits: reduced pollutant load; increased recharge to groundwater; and lower flow volumes and peaks. EPA Region 1 has identified stormwater recharge controls as being an effective way to achieve Total Maximum Daily Load (TMDL) phosphorus targets in the Charles River Watershed (EPA, 2007).

Since recharge controls have multiple benefits, it makes sense to optimize the technique for more than just pollutant removal. The use of stormwater recharge to augment streamflow can be optimized by exploiting the spatial lag time from recharge site to river and the temporal lag time between stormwater surplus (usually spring) and streamflow deficit (usually late summer). A three to six month lag time is considered suitable so that stormwater recharged in the spring can augment low streamflows in the late summer.

In this project, CRWA uses a method that was developed for the Town of Blackstone to help locate optimal areas for stormwater recharge (CRWA, 2005). The approach uses Geographical Information Systems (GIS) analyses and simple groundwater equations to identify optimal recharge zones. Identifying the best potential recharge areas involves the overlay of a number of GIS layers: upstream stormwater sources; sufficient lag time from recharge site to river; permeable, deep soils; available open space; town-ownership of land (if available), and the exclusion of drinking water protection areas or surface waters. An automated Optimal Stormwater Recharge Site Tool was also developed to allow the method to easily be applied other towns or watersheds.

A pilot application for the Town of Franklin was develop to demonstrate the method's potential utility for other watersheds in the state. The outcomes from the pilot project are the selection of the base layers, creation of a combined score map plus a detailed map that shows the best recharge areas. The outcome of REST is a custom ArcMap document that extracts the source layers for the overlay analysis, performs the overlays, then generates the scores map. The source layers are also available for creating a more detailed map with all the best areas (see last figure).

Suitability Layers

Identifying the best potential recharge areas involves an overlay of a number of suitability layers: upstream stormwater sources; sufficient lag time from recharge site to river; permeable, deep soils; available open space; town-ownership of land (if available), and the exclusion of drinking water protection areas or surface waters. These layers are discussed in more detail in this section.

Stormwater Potential Layer

Impervious area is composed of rooftops, roads, and parking lots. Much of the urban stormwater runoff and pollutant load comes from impervious area so usually good stormwater BMP sites will be situated downstream of significant areas of imperviousness. A site might have a great physical characteristics, but if is has no contributing impervious area, it will not receive much stormwater runoff, only minimal amounts from the upstream pervious areas.

Total impervious area (TIA, %) was calculated from the 2005 impervious surface layer available from MassGIS. The MassGIS layer is composed of 33 images with 1-m pixels of either 0 (not impervious) or 1 (impervious) for each pixel value. The 1-m images are very large and slow to process requiring one to work with a limited areal extent. The 1-m images were converted to 10-m real grids where the cell value is the fraction of the cell that is impervious (0 to 1) then merged into a single statewide layer. Testing on small subbasins (<5 square miles) gave less than a 1% error using the 10-m statewide grid versus the 1-m images in determining subbasin TIA.

The upstream total impervious area (UTIA, %) is the imperviousness in the upstream drainage area at any given point. To determine UTIA, CRWA used the watershed tools in ArcMap. A 10-m flow direction grid (Steeves, 2006) was used to determine the flow accumulation grid which is equivalent to the upstream drainage area. The flow accumulation tool was also used to determine the upstream impervious area by weighting the cells by the TIA grid. Dividing upstream impervious area by the total upstream area yields a grid as UTIA as a percentage (see Figure 1).

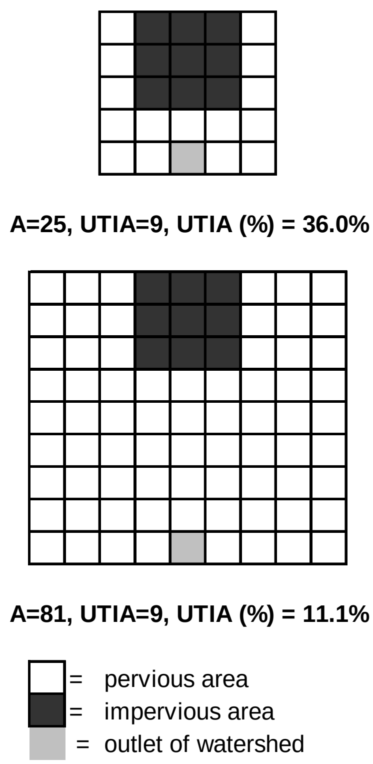


Figure 1. Diagram Showing UTIA Calculations

The UTIA (%) grid was converted to a polygon layer and then reclassified into 4 categories and scored (see Table 2) as follows

Score 1 = <5%
Score 2 = 5-15%
Score 3 = 15-35%
Score 4 = >35%

The outcome of this task is a polygon layer with four UTIA classes and scores (see Figure 2).

Lag Time Layer

The lag time from recharge site to the nearest surface water determines when the recharge is manifested in a stream as flow augmentation. The location of the recharge site is important since there will be a lag time between the supply of stormwater for recharge (highest in the spring) and the need of the river (flows lowest in the fall). Ideally, one would recharge where the lag time is from two to six months. The lag time is a function of the distance from recharge site to surface water and the conductivity of the aquifer material. Close proximity and highly conductivity results in short lag times and vice versa.

CRWA used the StrmDepl package from USGS (Barlow, 2000) to estimate the lag time from recharge site to surface water. This one-dimensional ground water flow package is designed to evaluate the stream depletion of a well on a nearby stream. If the recharge site is assumed to act like an injection well, and appropriate corrections are made for incomplete penetration of the recharge basin and the stream into the aquifer, then StrmDepl can be used to determine lag time from recharge site to nearest stream. The distance from recharge site to surface water can be increased to account for the lack of penetration.

Primary inputs to StrmDepl were distance and diffusivity (a measure of conductivity). Streambed resistance and lack of penetration was assumed to be equivalent to an additional distance of 200 ft. The lag time was calculated as the time for a 50% change in recharge rate to manifest itself in the predicted streamflow augmentation. Lag time can be estimated by simulating a constant recharge rate for a long time then suddenly turning it off, then measuring the time for the predicted stream augmentation to decline 50% from its starting value.

StrmDepl was run repeatedly to simulate many time lag scenarios for a range of distances and diffusivities. The relationship between the predicted lag time and inputs of distance and diffusivity was summarized by the following non-linear regression equation:

$$Lag_{50} = 95.65 * D^{-1.044} S^{1.465}$$

where Lag50 = the lag time from site to stream for a 50% change in recharge (days)
D = aquifer diffusivity (ft^2/day)
S = distance from site to surface water (feet)

This equation implicitly includes a 200 ft correction for lack of penetration of recharge basin and the stream into the aquifer.

Both streams and connected, non-forested wetlands were considered part of the surface water because they are hydrologically connected to the river system. A connected surface water body layer was developed from MassGIS stream centerline and 1:12k wetland data. Stream centerlines were buffered by 25 ft while non-forested wetlands were selected from the complete wetlands layer. The non-forested wetlands were then intersected with the buffered centerline data to select the non-forested wetlands that are connected to the stream network. The connected, non-forested wetland layer was then unioned to the buffered centerline data to create a combined polygon layer of connected surface water.

Distances from the nearest surface water were estimated using the Euclidian Distance function in ArcMap and resulted in a distance grid. Diffusivity was assigned to the MassGIS 1:250k surficial geology layer as in Table 1 and converted to a grid. A lag time grid was created using the above equation and the distance and diffusivity grids. The lag time grid was converted to a polygon lag time layer and then reclassified into 4 categories and scored (see Table 2):

Score 1 = < 7 days
Score 2 = 7-30 days
Score 3 = > 90 days
Score 4 = 30-90 days

The 30-90 day lag category has the highest ranking because it has the most potential benefit for using spring stormwater recharge to augment the low streamflows of late summer and early fall.

The outcome of this task was a scored polygon layer with four lag time classes (see Figure 3).

Table 1. Diffusivity by Surficial Geology

Code	Description	Depth (ft)	Diffusivity (ft^2/d)
1	Sand / Gravel		25,000
1	Sand / Gravel	0-50	12,500
1	Sand / Gravel	50-100	37,500
1	Sand / Gravel	100-200	75,000
1	Sand / Gravel	200+	150,000
1	Sand / Gravel	200-400	150,000
1	Sand / Gravel	400-500	225,000
1	Sand / Gravel	500-800	325,000
1	Sand / Gravel	800-1000	450,000
1	Sand / Gravel	>1000	600,000
2	Till / Bedrock		2,500
3	S Till / Sand		12,500
4	End Moraine		2,500
5	Large Sand	0-50	7,500
5	Large Sand	50-100	22,500
5	Large Sand	100-200	45,000
5	Large Sand	200-400	90,000
5	Large Sand	400-500	135,000
5	Large Sand	500-800	195,000
6	Fine-Grained		5,000
7	Floodplain Alluvium		7,500

Site Suitability Layer

Sites suitable for recharge BMPs are those with soils of high permeability and soil depths unrestricted by rock, impeding clay layers, or high water table. In extremely steep areas, it might also be necessary to add a slope criterion.

The latest soils data were extracted from the SSURGO database (USDA, 2007a). In SSURGO, each soil polygon or mapping unit identification number (MUID) can have a number of soil components (sub-soils) so the components must be aggregated to create a single attribute value per soil polygon or MUID. The average soil properties were aggregated using the SoilDataviewer V5.1 (NRCS, 2007b). The following parameters were aggregated and extracted as GIS layers for Norfolk County:

1) soil hydrologic class – dominant condition
2) depth to impeding layer of rock or clay – weighted average
3) depth to groundwater, full year– weighted average

The final step was to union the layers by MUID into a single layer with all three attribute fields.

The soil hydrologic class represents the soil runoff potential which can serve as a surrogate for both permeability and drainage. High class soils (e.g. A or B) have high permeability and good drainage. The depth layers were combined into a single depth restriction layer using the minimum of depth to impeding layer or depth to water table.

The soils layer was then reclassified into 4 categories and scored (see Table 2):

Score 1 = D- = D soils, any soil with depth restriction < 1 m, unrated soils
Score 2 = C+ = C soil with depth restriction > 1 m
Score 3 = B+ = B soil with depth restriction > 1 m
Score 4 = A+ = A soil with depth restriction > 1 m

The outcome of this task was a scored polygon layer of soil suitability with four suitability classes (see Figure 4). To make these soils data available statewide, the extraction process used for Norfolk County would have to be repeated and unioned to create a statewide layer. Areas where soil data was not available were assigned the lowest score of 1, however, site specific soil analysis could result in additional areas with higher scores.

Site Availability Layer

Sites available for recharge BMPs should ideally have sufficient open space for the installation of a surface BMP since a sub-surface BMP will be much more costly.

To develop the spatial site availability layer, the Open Space layer from MassGIS was used. The open space layer was then reclassified into 4 categories and scored (see Table 2). Scores were assigned based on the feasibility of incorporating recharge BMPs onto the designated land use.

Score 1 = unknown (X), underwater (U)
Score 2 = flood control (F), other (O)

Score 3 = conservation (C), habitat (Q), and water supply (W)
Score 4 = all remaining categories

Town-ownership of a potential recharge site is also considered very desirable because the town will not have to pay for the land used by the BMP thus lowering the stormwater BMP cost considerably. The town-owned layer for Franklin was obtained from the town GIS department. The town-owned land was scored as follows (see Table 2).

Score 0 = other land
Score 3 = town-owned land

The outcome of this task was two scored polygon layers of site availability with four site availability suitability classes and a town-owned land layer (see Figure 5). To make the town-owned layer available statewide, the data would have to be obtained for all towns and merged into a single statewide layer. Some towns do not have this layer readily available as a GIS layer.

Site Exclusion Layer

Not all sites are suitable for recharge BMPs. The latest Massachusetts stormwater standards (DEP, 2008) prohibit the use of Zone 1 and Zone A areas for recharge BMPs. In this analysis, a 25-ft buffer around the stream centerline and connected non-forested wetlands were also excluded because these areas are likely to permanently under water or very wet.

The statewide layers of Zone 1s and Zone As from MassGIS were combined into a single site exclusion layer and scored as follows (see Table 2):

Score 0 = Zone 1 / Zone A / Water
Score 1 = other land

This score is applied multiplicatively to exclude sites with a zero score and include all other sites.

The outcome of this task were two scored polygon layer showing Zone 1/A's and areas of Water that are excluded from potential recharge sites (see Figure 6).

Figure 2. Stormwater Potential for Recharge Sites in Franklin

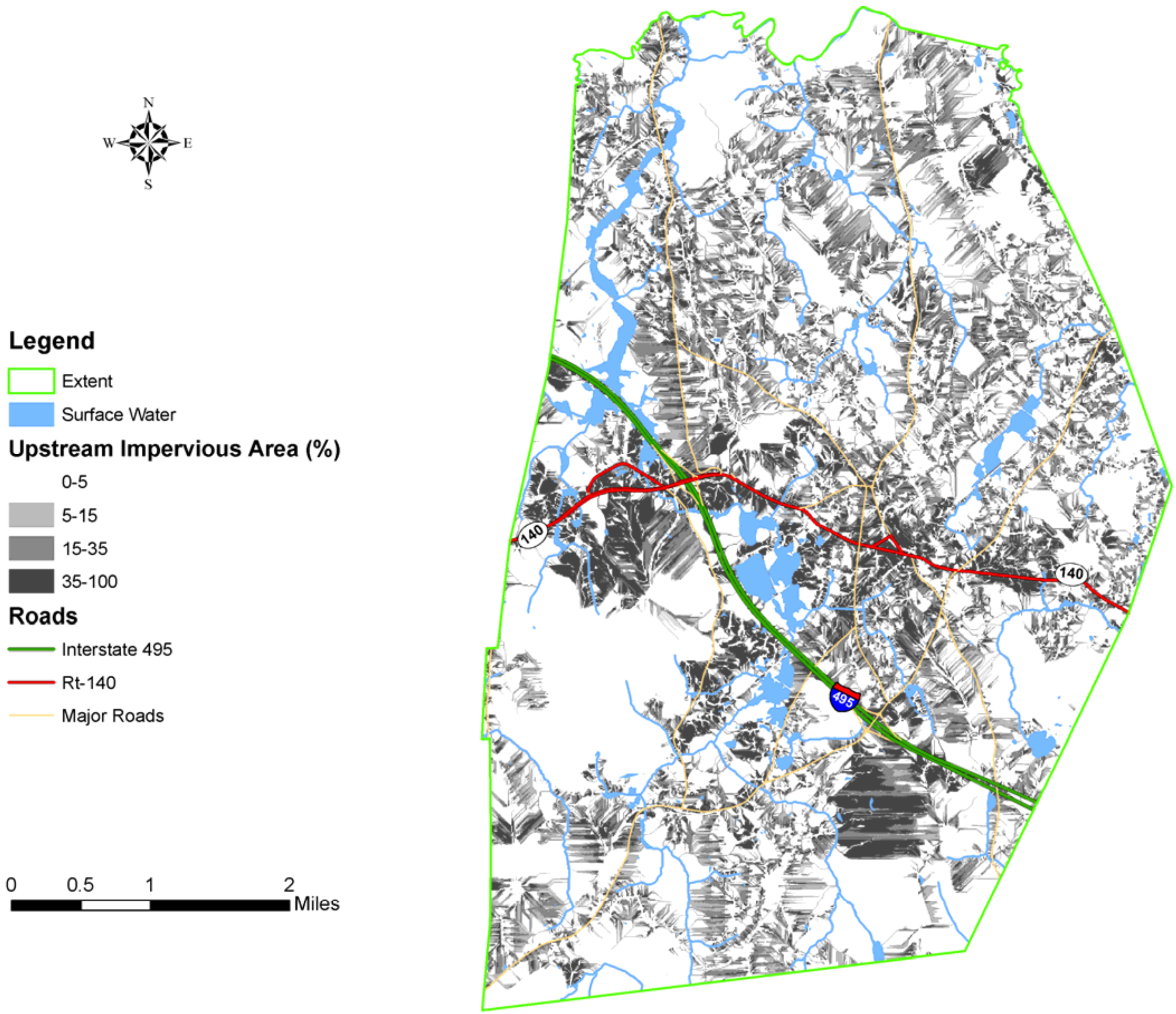


Figure 3. Lag Times for Recharge Sites in Franklin

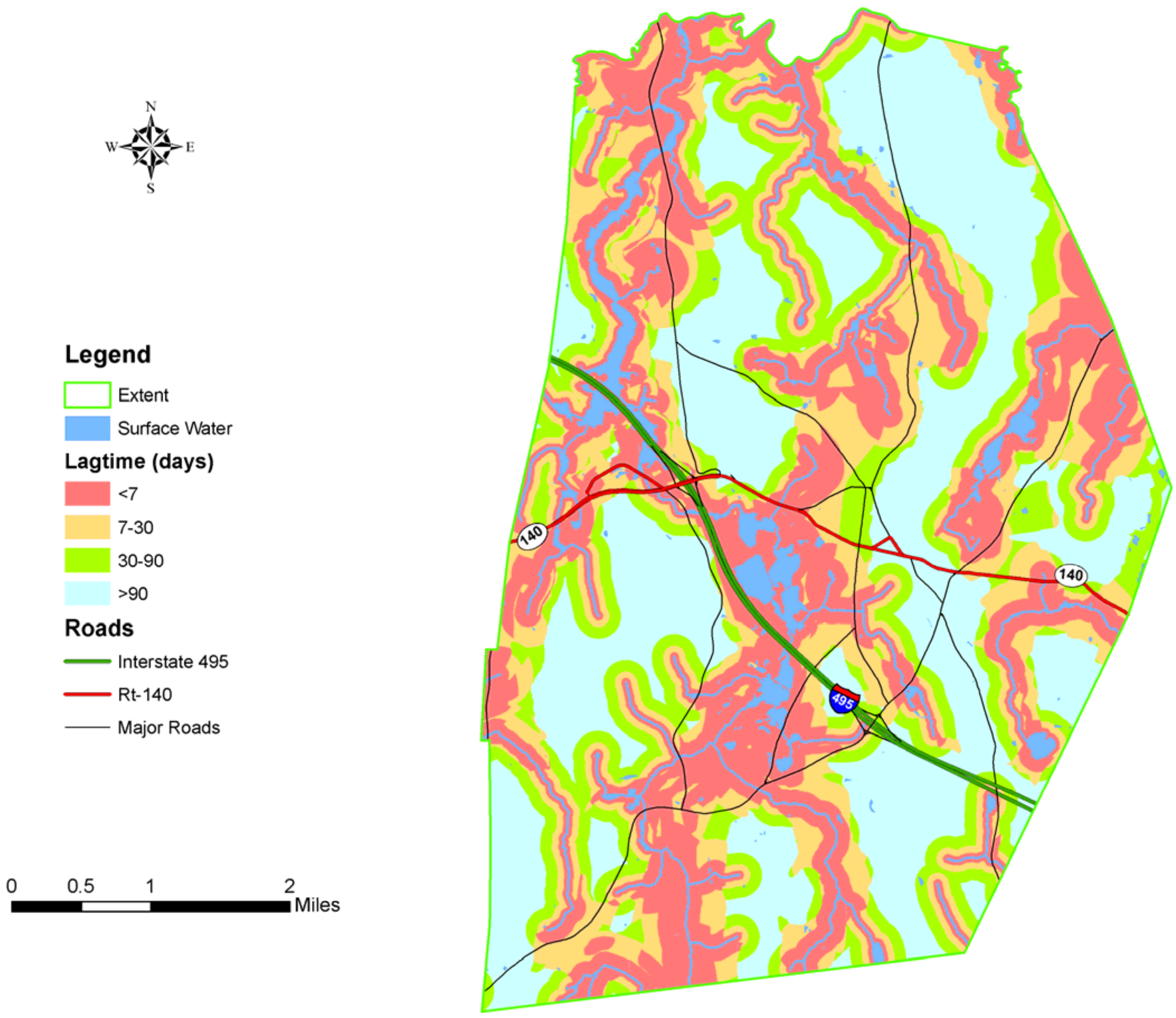


Figure 4. Soil Suitability for Recharge Sites in Franklin

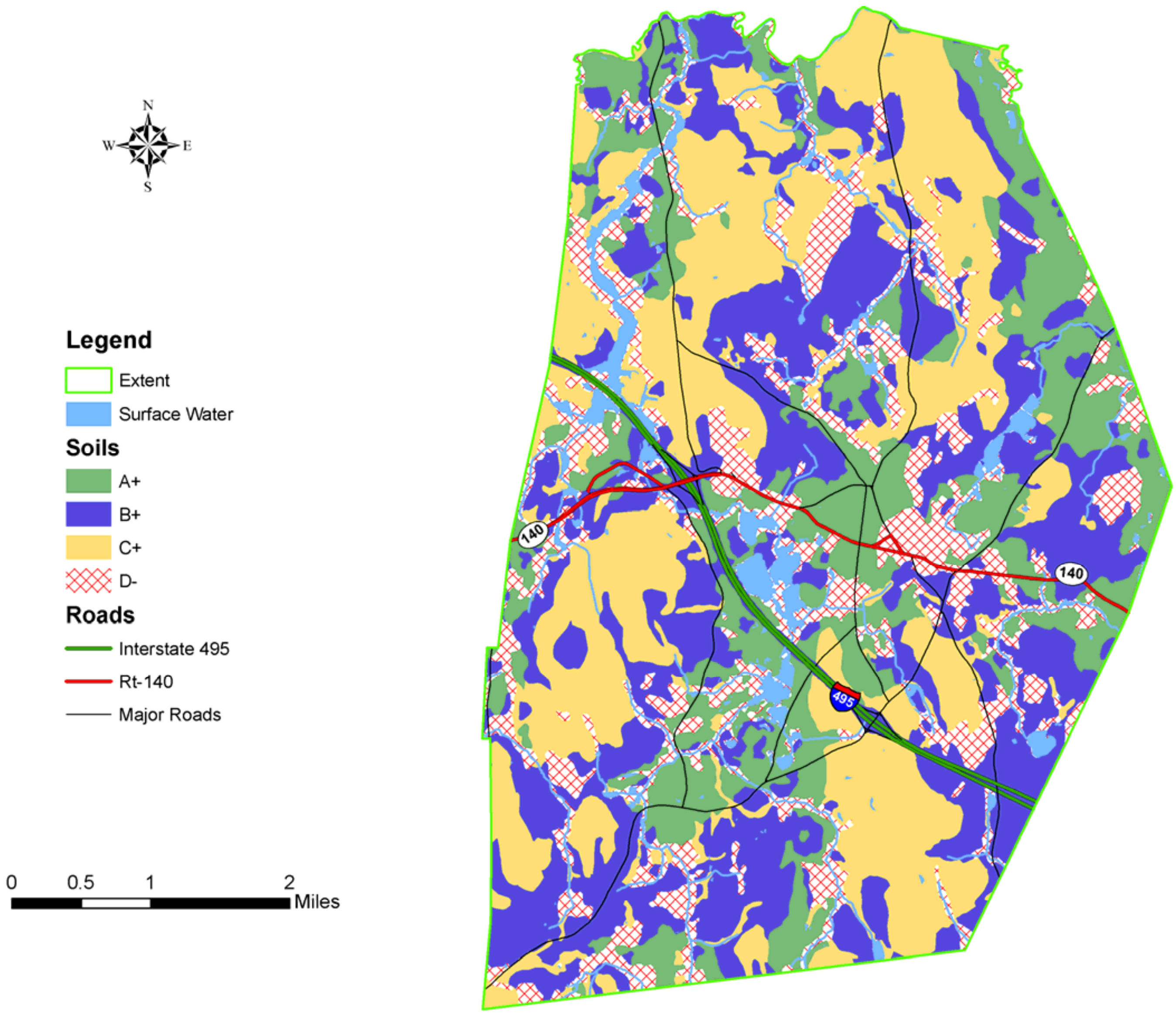


Figure 5. Site Availability for Recharge Sites in Franklin

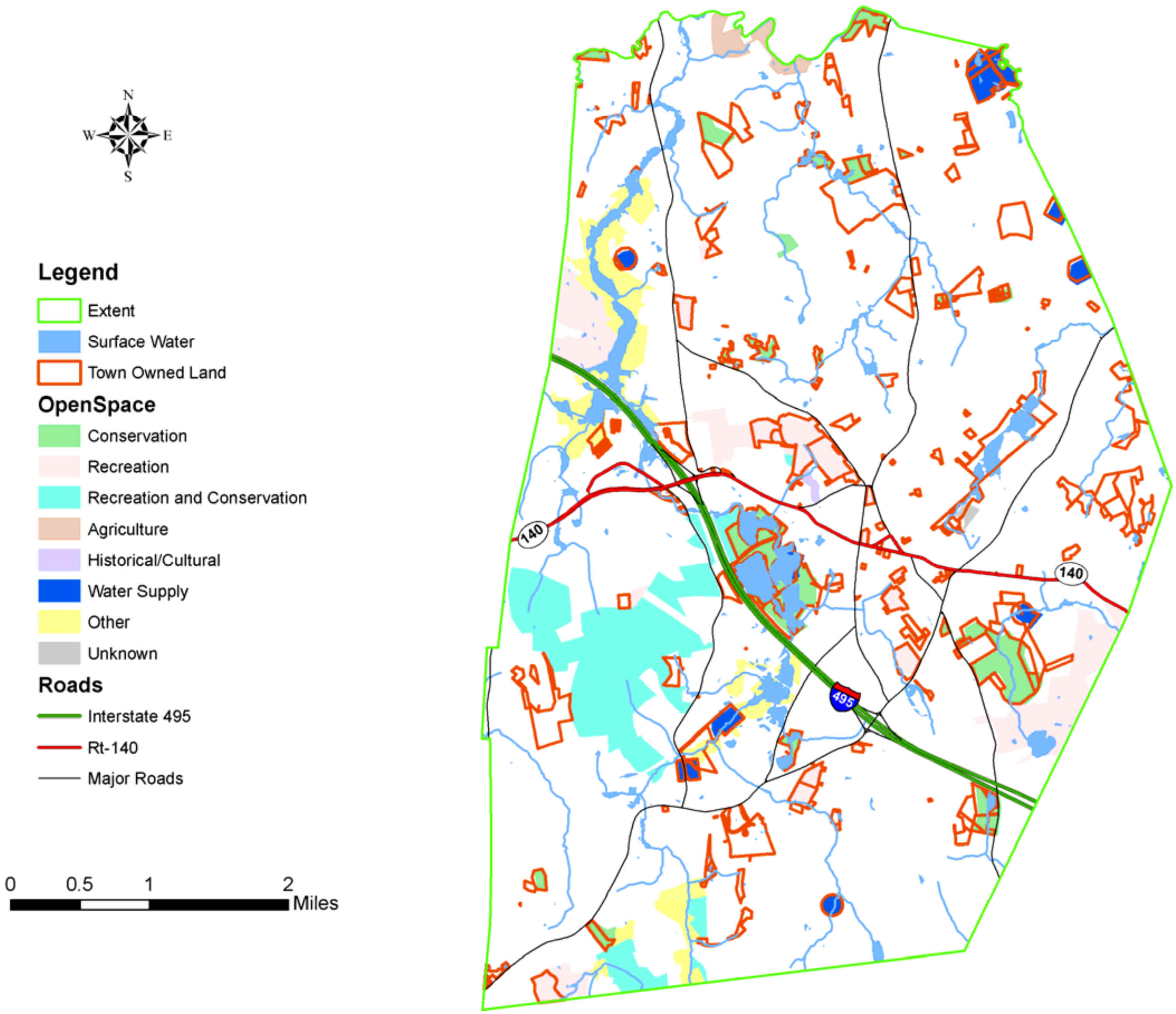
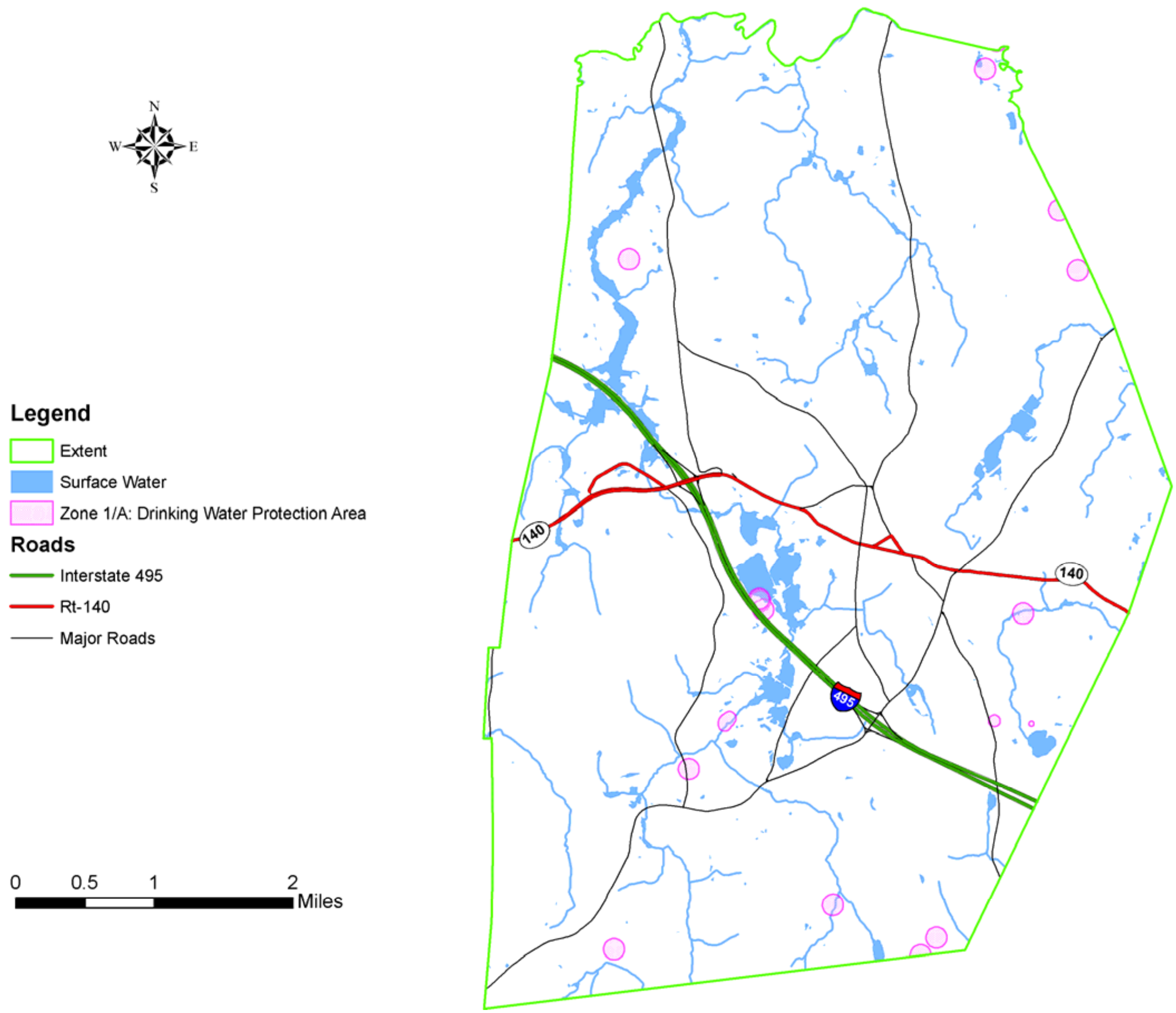


Figure 6. Site Exclusion for Recharge Sites in Franklin



Overlay Analysis

This analysis is a simple overlay analysis of the five suitability layers described in the previous sections. These layers are summarized in Table 2 with details on the scoring system. To minimize the generation of slivers, the layers were unioned together with a large XY tolerance (2 meters); however, the final layer was stored with the default XY tolerance (0.001 m). The scores were computed by adding the individual layer scores except for the exclusion layer for which the score (0/1) was applied multiplicatively to exclude sites with a zero score and included other sites.

Table 2. Summary of Suitability Layers and Scores

Item / Score	0	1	2	3	4
Upstream TIA (%)		0-5	5-15	15-35	35-100
Lag Time (days)		0-7	7-30	> 90	30-90
Soil Suitability		D-	C+	B+	A+
Open Space		X,U	F,O	C,Q,W	Others
Town-Owned Land	No			Yes	
Zone I / Zone A / Water[1]	Yes	No			

[1] multiplicative factor

The Scores results in Figure 7 show that the best locations for recharge in Franklin are mostly around the downtown area. To the northwest of town there is an area south and west of Main and Oak Streets while to the southeast of town the best area is a triangular wedge of land between Summer/King Streets and Upper Union Street.

The layers given in Figure 8 can be examined to determine the reasons why these areas score high as recharge sites. Not surprisingly, the downtown area has some of the highest values of upstream impervious area in the Town of Franklin. The high-score area also covers the western section of a zone with site-to-stream lag times greater than 30 days. Additionally, most of the downtown area has suitably permeable soils. Finally, there are tracts of available open space, especially to the northwest of the downtown, and many of these open areas are also town-owned.

The outcome of this task was two layers, one showing the combined scores and the other showing the best areas for recharge BMPs (see Figures 7 and 8). These layers can be used together to optimally site future stormwater recharge projects.

Figure 7. Scores for Recharge Sites in Franklin

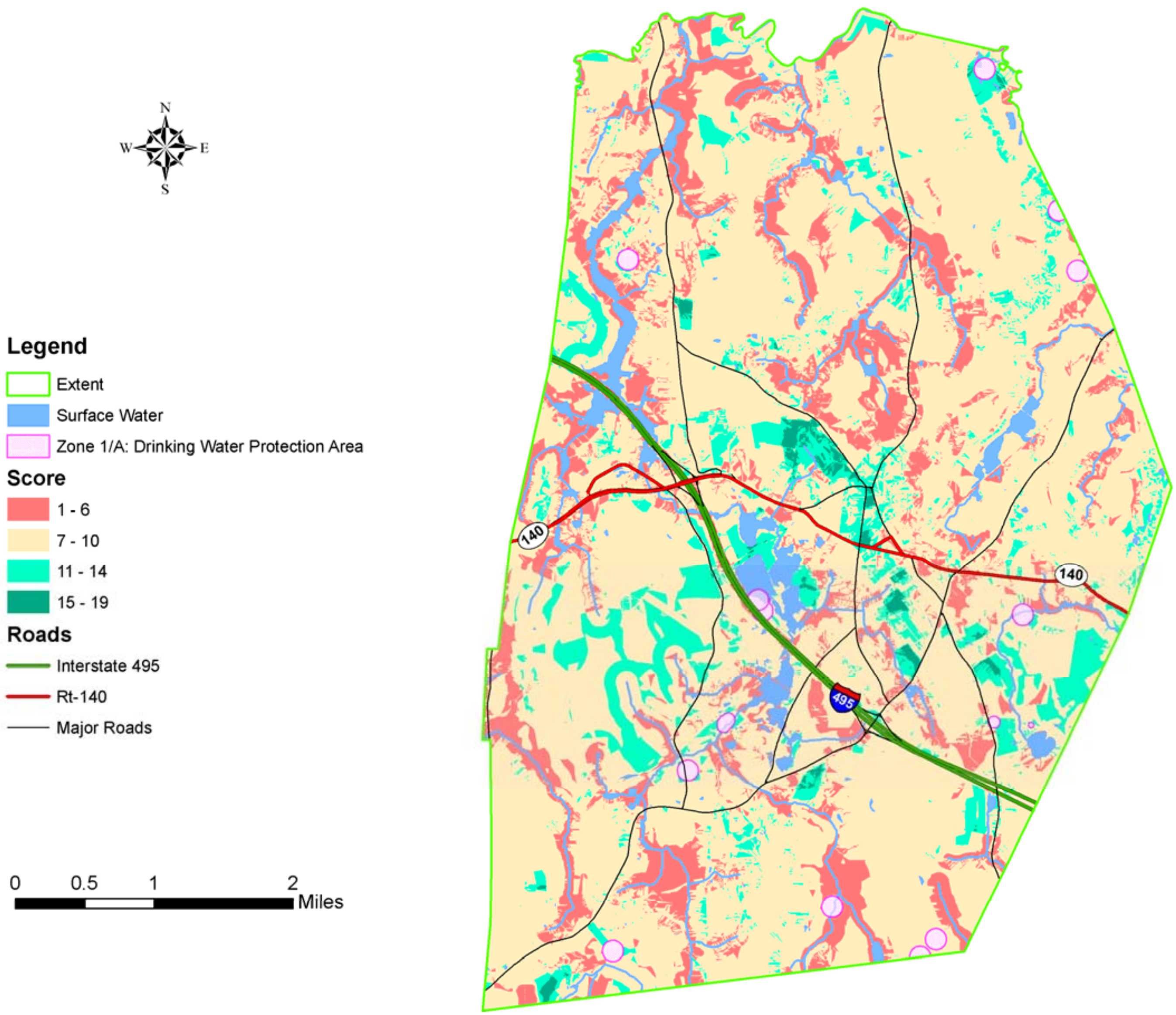


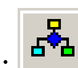
Figure 8. Optimal Locations for Recharge Sites in Franklin

Optimal Stormwater Recharge Site Tool

An automated Optimal Stormwater Recharge Site Tool was developed in ArcMap 9.3.1 using the Spatial Analyst Extension and Visual Basic for Applications (VBA) code. The resulting custom map document (OptimalSWSites.mxd) and tool are used in conjunction with associated statewide geodatabases. Additional ArcMap templates (labeled OptimalSWSites_Map2-8.mxd) use the output data layers to create the detailed maps (Figures 2-8) presented in this report.

The statewide data (Statewide.mdb geodatabase and Grid directory) include all the necessary base layers for the State of Massachusetts, except for the soils and town-owned land layers which are have not been have not been fully developed for the whole state. When the tool is applied outside of Franklin, the current statewide Soils layer (SW_Soils) will have to be expanded beyond Norfolk County. Similarly, the current town-owned layer (SW_TownLand) will have to be expanded beyond the Town of Franklin.

The user defines the analysis extent (a polygon called Extent), adds it to the map, and then runs the tool. The tool extracts the statewide date into a local geodatabase, then performs the overlays and calculates the recharge suitability scores, and finally creates maps of the best recharge sites for that extent. The time needed to run the tool is a function of the area of the extent—a single town like Franklin runs in about 20 minutes.

The Optimal Stormwater Recharge Site Tool does the following when the icon is clicked: 

1) Data extraction of all base layers:
    a. a 1000 ft buffer around the analysis extent
    b. local vector data to OptimalSWSites.mdb and grids to Grids directory
2) Generate suitability layers:
    a. stormwater potential layer using upstream impervious area
    b. lag time layer from connected surface waters and surficial geology diffusivity
    c. site suitability layer from soils layer
    d. site availability layer from open space layer and extract town-owned layer
    e. site exclusion layer from Zone I and Zone A layers
3) Create overlays and maps:
    a. overlay analysis by unioning source layers
    b. compute scores and create score map
    c. clip all layers from buffered extent to original extent
    d. symbolize and display layers

All relevant files are provided on an attached disc along with an installation ReadMe file. The OptimalSWSites folder can be copied to any directory as long as sub-directory structure is be preserved.

The outcome of this task is a custom ArcMap document and Optimal Stormwater Recharge Site Tool. The tool automatically extracts the source layers for the overlay analysis, performs the overlays, then generates the scores layer and output various maps.

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